Frequency and initiation of debris flows in Grand Canyon, Arizona

Peter G. Griffiths and Robert H. Webb
U.S. Geological Survey, Tucson, Arizona, USA

Theodore S. Melis
U.S. Geological Survey, Flagstaff, Arizona, USA

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[1] Debris flows from 740 tributaries transport sediment into the Colorado River in Grand Canyon, Arizona, creating rapids that control its longitudinal profile. Debris flows mostly occur when runoff triggers failures in colluvium by a process termed "the fire hose effect." Debris flows originate from a limited number of geologic strata, almost exclusively shales or other clay-rich, fine-grained formations. Observations from 1984 through 2003 provide a 20 year record of all debris flows that reached the Colorado River in Grand Canyon, and repeat photography provides a 100 year record of debris flows from 147 tributaries. Observed frequencies are 5.1 events/year from 1984 to 2003, and historic frequencies are 5.0 events/year from 1890 to 1983. Logistic regression is used to model historic frequencies based on drainage basin parameters observed to control debris flow initiation and transport. From 5 to 7 of the 16 parameters evaluated are statistically significant, including drainage area, basin relief, and the height of and gradient below debris flow source areas, variables which reflect transport distance and potential energy. The aspect of the river channel, which at least partially reflects storm movement within the canyon, is also significant. Model results are used to calculate the probability of debris flow occurrence at the river over a century for all 740 tributaries. Owing to the variability of underlying geomorphic controls, the distribution of this probability is not uniform among tributaries of the Colorado River in Grand Canyon. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1815 Hydrology: Erosion and sedimentation; 1821 Hydrology: Floods; 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* debris flows, mass wasting, geomorphology, Grand Canyon, Colorado River

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1. Introduction

[2] Debris flows are an important sediment transport process in 740 tributaries of the Colorado River in Grand Canyon, Arizona [*Webb et al.*, 2000] (Figures 1 and 9). Distributed along 444 kilometers of river between the Paria River and the Grand Wash Cliffs, these tributaries drain 12,000 km^2 of steep terrain between the North and South Rims of the canyon. Debris flows constrict the Colorado River at tributary junctures (Figure 2), raising the riverbed until main stem flows rework coarse-grain deposits and remove or reposition boulders [*Webb et al.*, 1989]. Boulders in the river are also subject to slow, long-term removal through dissolution and corrasion by smaller river flows.

[3] Despite reworking, the riverbed has risen at tributary confluences during the Holocene [*Webb et al.*, 1999a] and historically [*Melis et al.*, 1994; *Webb et al.*, 1999b] owing to debris flow deposition. The large boulders deposited in the river by debris flows form the core of rapids that modify the longitudinal profile and locally control the geomorphic framework of the present-day Colorado River in Grand Canyon (Figure 3) [*Webb*, 1996]. Rapids account for most of the vertical drop of the river in Grand Canyon, 66% of which occurs in only 9% of the river's length. Debris flows are a potential hazard to the white water recreational community, both by affecting navigation of the river and endangering people in narrow canyons or camped at the river. Debris flows have repeatedly damaged a water supply pipeline at Phantom Ranch (river mile 88 (Figure 1)), destroyed hiking trails, and destroyed vehicles and threatened lives at Diamond Creek (river mile 226 (Figure 1)) and elsewhere [*Melis et al.*, 1994].

[4] An essential step toward estimating the amount of sediment transported to the river by debris flow is quantifying the frequency at which debris flows reach the river. Debris flow frequencies can be used in conjunction with separate magnitude (volume and particle size) data to calculate the amount of sediment from debris flows that enters the river [*Webb et al.*, 2000]. This paper approaches the problem by calculating the rate at which debris flows reach the Colorado River in Grand Canyon for two time

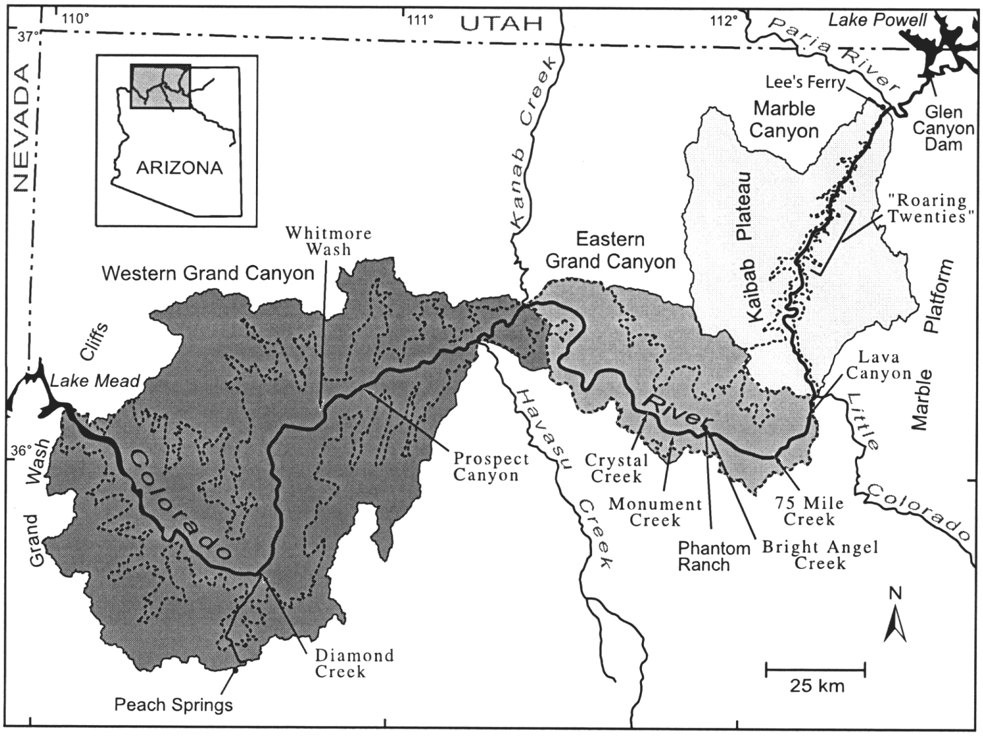

Figure 1. Colorado River in Marble and Grand Canyons, Arizona. The shaded areas represent the drainage area of the Colorado River, less that of the Little Colorado River and Kanab and Havasu Creeks, between the Paria River and the Grand Wash Cliffs, divided into major geomorphic reaches. Canyon rims are indicated by the dotted line.

periods: the recent past (1984–2003), as observed directly for all 740 tributaries, and a historic period (1890–1983), as preserved in photographs for a subset of 147 tributaries. Historic probabilities of debris flow occurrence are estimated for all 740 tributaries by modeling the known frequency distribution with drainage basin parameters observed to control the process by which debris flows initiate and travel to the river. Owing to the limitations of the initial data sets and the focus on geomorphic change in the river corridor, this study evaluates only those debris flows that reach the Colorado River.

2. Debris Flows and the Colorado River in Grand Canyon

[5] The 20th century occurrence of debris flows in Grand Canyon is relatively well known. *Cooley et al.* [1977] examined debris flows that occurred in 1966 in several tributaries of the Colorado River, including Lava Canyon and Crystal Creek (river miles 65.5-R and 98.2-R) and inferred some frequency information from damage to archaeological sites. On the basis of analysis of aerial photography, *Howard and Dolan* [1981] reported that tributary floods had affected 25% of all debris fans in one reach of the Colorado River between 1965 and 1973. *Webb et al.* [1989] reported magnitude and frequency information for three tributaries of the Colorado River. *Melis et al.* [1994], updated by *Webb et al.* [2000], report preliminary magnitude and frequency data for debris flows between 1984 and 1998 in Grand Canyon, with magnitudes of single events ranging from 300 to 65,000 m^3. The information presented in this paper replaces the preliminary information given by *Webb et al.* [2000].

[6] Many researchers have described the rapids that dominate the river corridor of Grand Canyon [*Leopold*, 1969; *Howard and Dolan*, 1981; *Kieffer*, 1987]. Other researchers have more fully documented the role of debris flows in the creation and maintenance of debris fans and rapids [*Cooley et al.*, 1977; *Webb*, 1996; *Webb et al.*, 1989, 1999a, 2003; *Melis et al.*, 1994]. Given their episodic nature, debris flows result in large modifications to debris fans and associated rapids over very short time periods, in most cases minutes to hours [*Webb et al.*, 1988, 1999a]. River reworking of newly aggraded debris fans, which was extensive on the unregulated river [*Melis*, 1997], occurs on a limited basis on the regulated Colorado, typically during maximum power plant releases or intentional flood releases from Glen Canyon Dam [*Webb et al.*, 1999b]. The reduction of the size of the annual flood on the Colorado River since 1963 limits the river's competence to extensively erode newly deposited debris that continues to accumulate on debris fans. *Howard and Dolan* [1981] reported that this decrease in flood size represents a fourfold decrease in the sediment transport potential of the river. Tributaries downstream from Glen Canyon Dam are unregulated, and debris flows are now the effective agent of change in the river corridor [*Howard and Dolan*, 1981; *Webb et al.*, 2000]. As a result, the "quasi-equilibrium" [*Langbein and Leopold*, 1964] that may once have existed between the river and its tributaries in the predam era has shifted in favor of the

Figure 2. Morphology of Granite Rapid, a typical debris fan and rapid of the Colorado River in Grand Canyon. 1, tributary debris fan; 2, boulder-controlled rapid; 3, debris bar (island); 4, riffle or rapid caused by debris bar. (Photograph by the Bureau of Reclamation, 1967). The arrow indicates the direction of river flow.

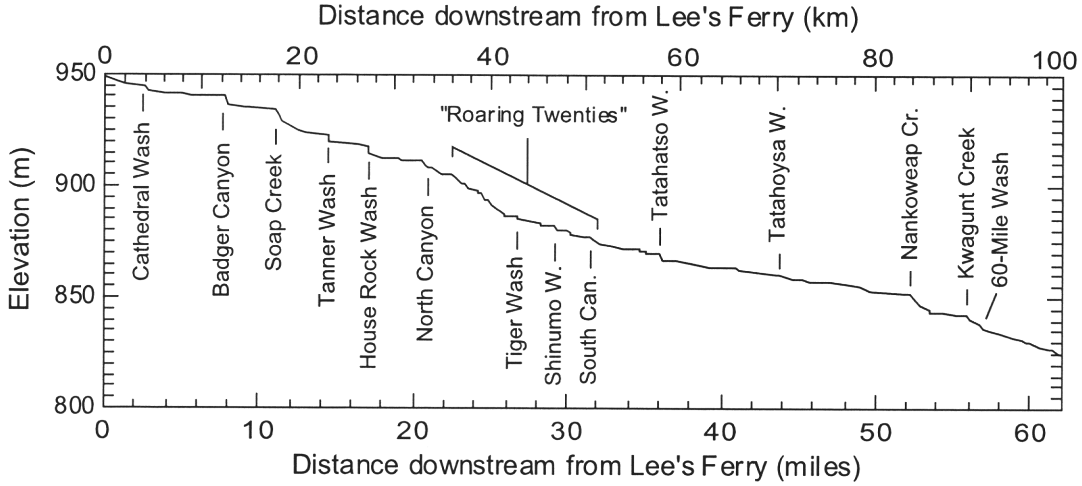

Figure 3. Longitudinal profile of the Colorado River between Lee's Ferry, Arizona, and the Little Colorado River, surveyed in 1923 [*U.S. Geological Survey*, 1924]. Rapids are clearly evident as the profile drops at major tributaries. The vertical exaggeration is 325.

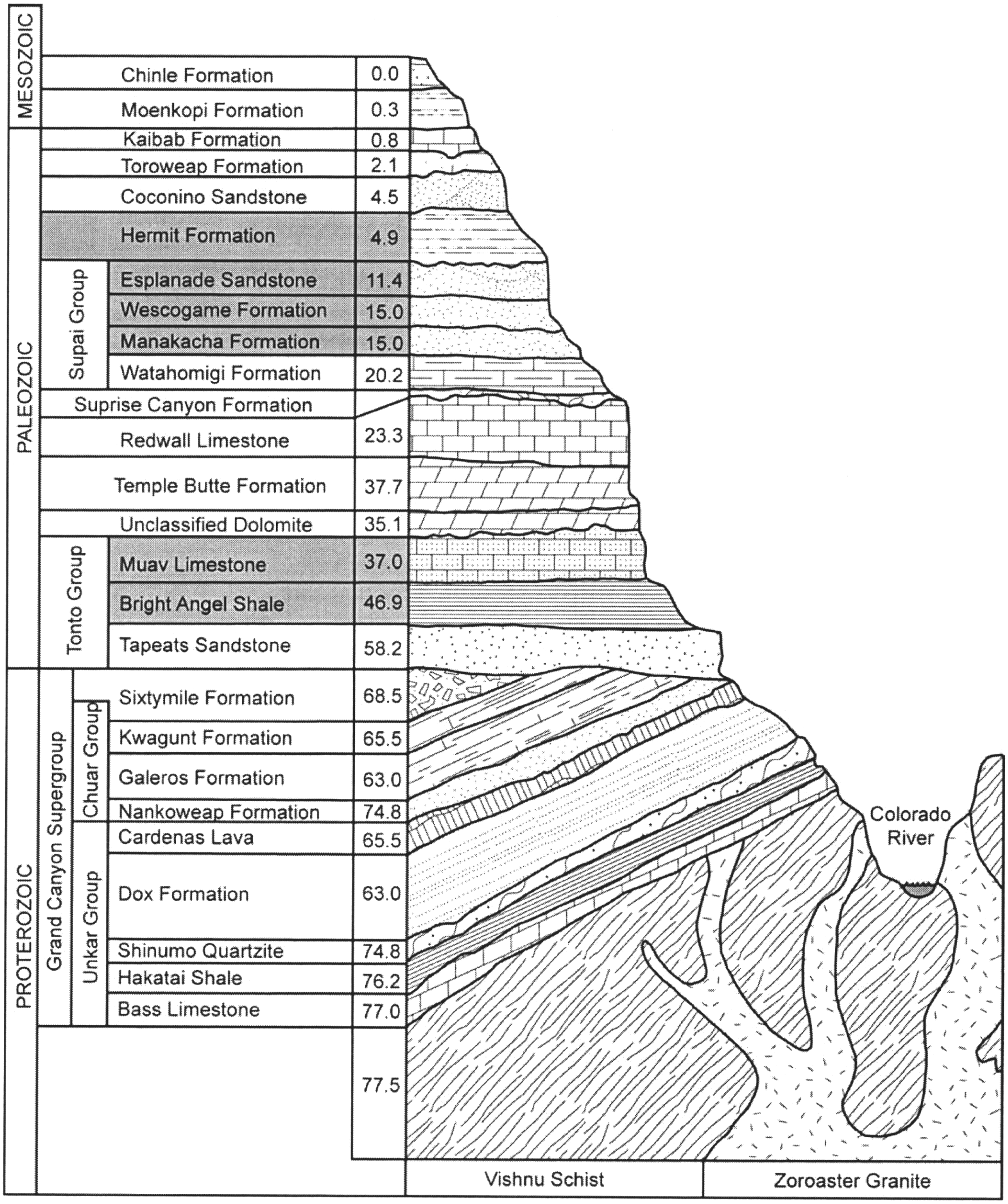

Figure 4. Stratigraphic column showing rocks exposed in Grand Canyon [modified from *Billingsley and Elston*, 1989]. Principal sources of debris flows that reach the Colorado River are shaded in gray.

tributaries since 1963, resulting in increasing aggradation on debris fans [*Howard and Dolan*, 1981].

3. Setting

[7] In this paper we use the general term "Grand Canyon" to refer to all 444 km of canyon through which the Colorado River flows between the Paria River and the Grand Wash Cliffs (Figure 1). For continuity with traditional practices and established reference points we locate tributary confluences and other features by river mile [*Stevens*, 1990]. A stratigraphic column depicting bedrock exposed in Grand Canyon appears in Figure 4.

[8] Elevations in Grand Canyon range from 975 to 2804 m above sea level at the rim and from 939 m to 402 m along the river. The climate is semiarid to arid, producing a wide range of annual and seasonal precipitation [*Griffiths et al.*, 1997; *Webb et al.*, 1999a]. In general, moisture and storm systems travel across Grand Canyon from southwest to northeast, and the canyon morphology is frequently observed to steer storms locally owing to the combination of steep topography and hot air rising from the canyon bottom. Strong orographic lifting occurs in the vicinity of the Kaibab Plateau (Figure 1), with more rainfall falling at higher elevations, particularly on the North Rim.

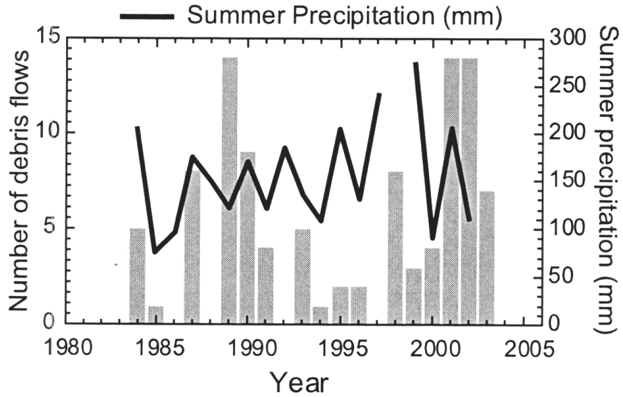

Figure 5. Number of debris flows in Grand Canyon and summer precipitation at Grand Canyon National Park Airport. Rainfall records are missing for the summer of 1998 [modified from *Griffiths et al.*, 1997].

[9] Most debris flows in Grand Canyon are initiated during intense summer convective thunderstorms created by moist air advected into the region from either the Gulf of Mexico or the Pacific Ocean [*Melis et al.*, 1994; *Griffiths et al.*, 1997]. Fewer but larger debris flows occur during unusually warm winter frontal systems [*Cooley et al.*, 1977; *Webb et al.*, 1989]. In contrast to summer thunderstorms, warm winter storms cover much larger areas and can deliver heavy rain and snow over several days [*Hansen and Schwarz*, 1981; *Hirschboeck*, 1985; *Webb and Betancourt*, 1992]. These storms are strongly orographic (e.g., 1966 event [*Cooley et al.*, 1977]), generally travel from southwest to northeast across the canyon, and affect several drainage basins at the same time, causing multiple slope failures, high-volume debris flows, and sustained runoff [*Melis et al.*, 1994]. Quantitative data on the intensity and duration of precipitation that triggers debris flows in Grand Canyon is extremely sparse due to the limited number of long-term rain gauges in the area, few of which are in these drainage basins [*Webb et al.*, 2000].

[10] *Webb et al.* [2000] identified 736 geomorphically significant tributaries of the Colorado River in Grand Canyon between Lee's Ferry and the Grand Wash Cliffs (river mile 0–276), excluding the four largest tributaries of the Paria and Little Colorado Rivers and Kanab and Havasu Creeks. These tributaries have the potential to produce debris flows that affect the geomorphology of the river channel. In this paper we define geomorphically significant tributaries as those which (1) have drainage areas larger than 0.1 km^2, (2) have a channel network that terminates at the river in a single channel, and (or) (3) display clear evidence of past and (or) present debris flow activity. Using these criteria, we add 12 tributaries and delete 8 from the data set of *Webb et al.* [2000] for a total of 740 tributaries (Figures 1 and 9).

4. Records of Debris Flow Frequency in Grand Canyon

4.1. Direct Observations (1984–2003)

[11] We directly observed and compiled the observations of other river runners on debris flows, rockfalls, or significant streamflow floods that occurred along the river in Grand Canyon from 1984 to 2003, updating the work of *Melis et al.* [1994] and *Webb et al.* [2000]. These data provide a complete record of debris flows that reached the Colorado River from all Grand Canyon tributaries over 20 years (Figure 5). During this period an average of 5.1 debris flows occurred per year for a total of 101 events at 84 tributaries (Table 1; Figure 5). A total of 14 debris flows occurred in 2001 and again in 2002, the most prolific 2 year period in the record. Many of these debris flow deposits extended into the river, and five created major changes in rapids. As depicted in Figure 5, the annual number of debris flows is not related to total summer precipitation, underscoring the influence of individual storms and suggesting that antecedent moisture has little effect on debris flow occurrence [*Griffiths et al.*, 1997].

[12] Most debris flows occurred in Marble Canyon or eastern Grand Canyon, with one notable exception at Lava Falls Rapid in 1995 [*Webb et al.*, 1999a]. Several tributaries delivered more than one debris flow to the river between 1984 and 2003; for example, 75 Mile Creek had four debris flows and Monument Creek had three. Multiple debris flows within a drainage basin suggest that slope and channel destabilization caused by the initial event may lead to repeated events until either the destabilized sediment is removed or sufficient respite from severe storms allows stabilization. Several debris flows can result from a single thunderstorm of sufficient size to cover adjacent tributary canyons simultaneously. Overall, our observations indicate that the frequency of debris flow deposition along the Colorado River in Grand Canyon has not been uniform in the recent past.

4.2. Repeat Photography (1890–1983)

[13] Repeat photography has been used in numerous studies in Grand Canyon to document long-term changes in both terrestrial ecology and geomorphology [*Turner and Karpiscak*, 1980; *Stephens and Shoemaker*, 1987; *Melis et al.*, 1994; *Webb*, 1996; *Webb et al.*, 1989, 1999a]. Between 1989 and 2002 (mostly between 1990 and 1994) we matched a total of 1365 historic photographs of the river corridor dating to as early as 1871. These photographs were interpreted for evidence of debris flow occurrence in the form of changes to debris fans at 160 tributaries (e.g., Figure 6). The year with the most abundant, widespread

Table 1. Frequency of Observed Debris Flows in Grand Canyon, Arizona

Period	Interval, years	Debris Flows (n)	Tributaries in Sample			Percent of Population	Debris Flows per Year	
			Debris Flows	No Debris Flows	Total		Sample	Population
1890–1983	94	93	84	63	147	19.9	1.0	5.0
1984–2003	20	101	84	656	740	100.0	5.1	5.1

A. B.

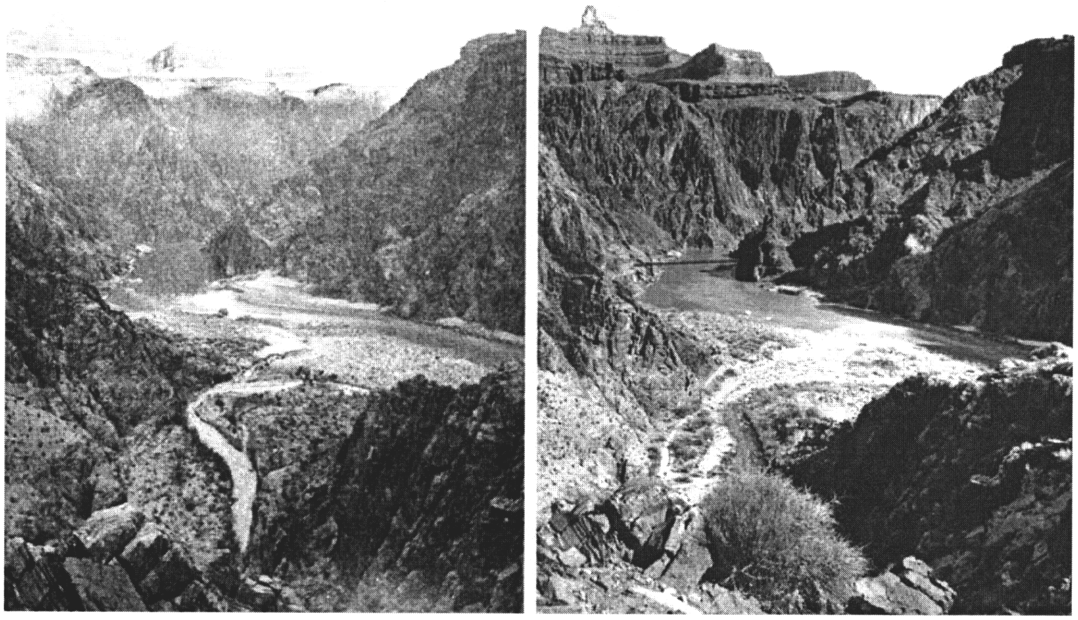

Figure 6. Replicate photographs of the debris fan at Bright Angel Creek (river mile 87.8-R). (a) 5 February 1890. Bright Angel Creek, a perennial stream, has its headwaters on the North Rim. In 1890 the channel is distinct, relatively narrow, and hooks right to join the Colorado River beyond the cliff at the lower right (photograph by R. B. Stanton). (b) 13 February 1991. Beginning in December 1966, several debris flows here have significantly changed the debris fan, moving the edge of the debris fan closer to the Colorado River (photograph by T. S. Melis).

coverage is 1890, when the well-documented Stanton expedition occurred [*Webb*, 1996]. To create a data set that is independent from direct observations (section 4.1), debris flows that occurred after 1984 were not included in this count, creating a partial record of debris flow occurrence along the river corridor from 1890 through 1983.

[14] We also analyzed several sets of low-altitude aerial photographs taken between 1935 and 1984 and ranging in scale from 1:3,600 to 1:31,800. In 1935, aerial photographs were taken of river miles 0–61 and 225–280; a second set of unrelated photographs, taken in November 1935, recorded river miles 87–129; and a third set was taken in 1938 and recorded river miles 211-280. Spatially continuous aerial photography of the river corridor was taken in 1965, 1973, 1980, and annually between 1984 and 2002. The combination of repeat and aerial photography resulted in the detection of 107 debris flows that occurred between 1890 and 1983 at the mouths of Grand Canyon tributaries. Combining these results with observations between 1984 and 2003, 210 debris flows are known to have occurred historically along the river in Grand Canyon.

[15] To determine the frequency of debris flows at the river from 1890 through 1983, we interpreted the 1890 Stanton photographs and their matches for evidence of debris flow occurrence at 147 debris fans. These photographs reveal that debris flows occurred at 84 tributaries (Table 1), indicating that 57% of the tributaries generated one or more events from 1890 through 1983. Because any of these 84 tributaries could have delivered more than one debris flow, we used additional data, including photography and written accounts, to identify a total of 93 debris flows from the 84 tributaries over a century period (0.99/yr (Table 1)). Only 6% of tributaries produced two or more debris flows in this period, including five at Lava Falls Rapid [*Webb et al.*, 1999a]. Taking this data set as an unbiased sample of the entire population of 740 tributaries, we extrapolate the rate of debris flow occurrence at the river to 5.0/yr for all tributaries from 1890 through 1983, which is nearly identical to the 5.1/yr frequency observed between 1984 and 2003. This rate may be a minimum because smaller deposits created during the predam period (pre-1963) may have been completely reworked during annual floods.

5. Initiation of Debris Flows in Grand Canyon

[16] Worldwide, rainfall-induced debris flows typically are initiated when rainfall of sufficient duration and intensity saturates unconsolidated sediments, increasing pore pressure until slope failure results [e.g., *Caine*, 1980; *Neary and Swift*, 1987; *Wieczorek*, 1987; *Anderson and Sitar*, 1994]. Debris flows in Grand Canyon are also triggered by extreme precipitation, but most debris flows that reach the river result from bedrock avalanches or the failure of colluvium undercut by flowing water rather than saturation-type failures (see section 5.1 below). Unlike debris flows

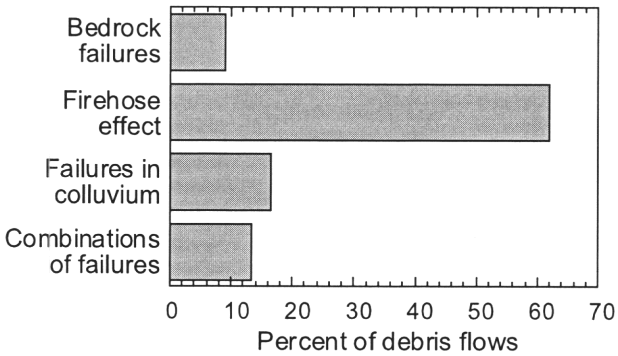

Figure 7. Relative frequency of initiation mechanisms for selected debris flows from 1939 through 2003 in Grand Canyon (n = 68) [modified from *Griffiths et al.*, 1997].

described in more humid regions, media saturation occurs after slope failure through the mixing of water and sediment. Grand Canyon debris flows that reach the river average 14–15% water content by weight (n = 55), indicating that these flows are at the drier end of recorded debris flows worldwide (9–50% by weight [*Costa*, 1984]). Nevertheless, these debris flows have been observed to travel as far as 22 km from their initiation point [*Webb et al.*, 1989].

[17] This particular mode of debris flow initiation requires the crossing of a critical energy threshold following failure. In order for a slope failure to transform into debris flow, the failed sediment must have sufficient energy to maintain motion as a dry mass movement until mixed with water. Once mixing occurs, the material is transported by the more energy-efficient combination of granular and fluid flow that characterizes debris flow [*Iverson*, 1997]. Failures with insufficient initial energy cannot become debris flows and do not travel far from the point of initiation [*Melis et al.*, 1994]. Once formed, debris flow transport is limited primarily by gradient and channel width, which controls critical flow depth.

[18] Evidence for an energy threshold in the formation of debris flows is apparent in upper Marble Canyon. In this case, debris flows are not yet transport limited by gradient or channel width because the source material, the Hermit Formation, is adjacent to the river corridor in the cliff face. Instead, debris flows are limited primarily by the critical threshold of initiation. The frequency of debris flows increases at about river mile 20.0, as evidenced by the beginning of the "Roaring Twenties," a set of some of the most closely spaced rapids in Grand Canyon (Figures 1 and 3). The lithology and morphology of the canyon have not changed substantially at this point, and neither has the density of tributaries (1.7/km in this reach compared to 1.6/km for all of Marble Canyon). What has changed is the elevation of the Hermit Formation, which has risen to heights of more than 100 m above the river. At this height the source material presumably has acquired sufficient potential energy to exceed the critical threshold of initiation for most debris flows. Downstream, the Hermit Formation is higher in the canyon walls and farther from the river, and debris flows again are transport limited as gradient becomes a controlling factor. Debris flow frequency is reduced, and the density of rapids decreases (Figure 3).

5.1. Mechanisms of Initiation

[19] In Grand Canyon, *Melis et al.* [1994] classify debris flow initiation by four mechanisms of slope failure: (1) direct failure of weathered bedrock; (2) the "fire hose effect" [*Johnson and Rodine*, 1984], in which streamflow runoff falls directly onto colluvium at the base of cliffs; (3) direct failure of colluvium by saturation or undercutting along channels; and (4) combinations of these mechanisms. We apply this classification scheme to our observation data to estimate the current relative frequency of each initiation mechanism in generating debris flows which reach the river (Figure 7). These data include 51 debris flows observed from 1984 through 2003 and 17 debris flows that occurred between 1890 and 1983. Owing to the steep, commonly inaccessible topography, initiation points for many historical debris flows could not be determined.

[20] The fire hose effect is the most common initiation mechanism (62% (Figure 7)). This mechanism requires streamflow over a waterfall or pourover that falls on preexisting colluvial wedges at the base of cliffs, causing failure and subsequent mixing to create a slurry. Presumably, repeated debris flow occurrence is at least partially dependent on regeneration of these wedges following their partial or total removal during an event. In contrast, direct failure of colluvium owing to saturation or undercutting adjacent to channels accounts for only 16% of the debris flows in this period (Figure 7), indicating that 78% of debris flows initiate in colluvium. Direct failure of colluvium typically produces the smallest debris flows, which do not travel long distances [*Melis et al.*, 1994].

[21] In contrast, debris flows initiated by bedrock failures tend to be the least numerous (9%) but are among the largest in Grand Canyon [*Webb et al.*, 1988]. In these few cases, direct failure of weathered Paleozoic shales and sandstones, most often in either the Hermit Formation or Supai Group, is triggered by intense, localized rainfall from convective summer thunderstorms or prolonged winter precipitation [*Cooley et al.*, 1977]. This rockfall, in turn, entrains other sediment as it moves downslope, mixing with storm runoff to form a debris flow.

5.2. Source Material

[22] Debris flow source sediments in Grand Canyon consist primarily of weathered and jointed bedrock, wedges of colluvial material on steep slopes or beneath normally dry waterfalls, and sediment stored in or adjacent to channels. Numerous exposed sedimentary strata, ranging from shale to sandstone and limestone, provide a variety of bedrock sources in a setting of high topographic relief (Figure 4). Colluvium and other poorly sorted sediment accumulate in channels. Once initiated, debris flows in Grand Canyon often increase in volume as they move toward the river by entraining sediments from terrace deposits or channel beds [*Melis et al.*, 1994; *Webb et al.*, 1999a].

[23] Despite the canyon-wide abundance of potential source material for debris flow, debris flows that have reached the river in Grand Canyon start at specific strata in the geologic section (Figure 4). For 67 of the 210 debris

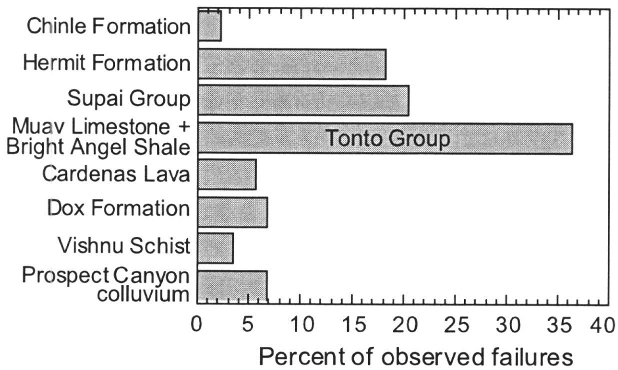

Figure 8. Relative frequency of the location at which slope failures in bedrock or colluvium resulting in debris flows that reach the river (1939 through 2003) have occurred in Grand Canyon (n = 101). Location is given according to bedrock formation in the stratigraphic section (Figure 4), except for "Prospect Canyon colluvium," which refers to debris flows that originated in colluvium at the base of the waterfall in Prospect Canyon. Formations are listed in downstream order of exposure.

flows that occurred between 1890 and 2003 we identified the locations of 88 slope failures (19 debris flows were the result of multiple failures) (Figure 8). Eight formations are represented, with the combined Bright Angel Shale and Muav Limestone of the Tonto Group accounting for the largest number of failures (35%). Four lithologic units (16% of the 25 exposed formations) account for 75% of the slope failures: the Bright Angel Shale, Muav Limestone, Supai Group, and Hermit Formation. Once exposed in Marble Canyon, these four Paleozoic strata are present throughout Marble and Grand Canyons as debris flow source areas.

[24] The remaining 25% of debris flow–generating slope failures occur in material that is of limited geographic extent or are infrequent. Failures in the local Sandstone/Mudstone Member of the Chinle Formation [*Phoenix*, 1963] only occur along the first 20 miles of Marble Canyon in 14 tributaries that extend above the rim and drain Mesozoic bedrock (e.g., Badger Canyon, mile 7.9). The Proterozoic Dox Sandstone and Cardenas Lava are exposed for a limited reach in upper eastern Grand Canyon between river miles 66 and 79. The remaining two categories represent atypical events. Failures in the Vishnu Schist have been observed to result in debris flows at river level on only two occasions. All six debris flows at Lava Falls Rapid (the highest frequency of any tributary in Grand Canyon) are not associated with a specific formation but result from the unusual presence of a large cone of mostly volcanic debris deposited at the head of Prospect Canyon and associated with the offset of the Toroweap fault [*Webb et al.*, 1999a].

[25] Considering the energy threshold that slope failures must exceed to become debris flows, high-angle, cliff-forming units, such as the Redwall Limestone, might be expected to generate the most debris flows in Grand Canyon. This is not the case, as the eight formations associated with debris flows that reach the Colorado River are mostly low-angle, slope-forming units, such as the Hermit Formation and Bright Angel Shale (Figure 4). These units form slopes because they contain an abundance of fine-grained, clay-rich, and poorly indurated sedimentary members (the Cardenas Lava contains fluvial sandstone interbeds) which we refer to generally as shales. Shales provide an abundance of fine particles and clay minerals that are essential to the mobility and transport competence of debris flows.

[26] Silt and clay mix with water to form the highly viscous pore fluid that mediates intergranular collisions and differentiates true debris flow from dry granular flow [*Beverage and Culbertson*, 1964; *Rodine and Johnson*, 1976; *Iverson*, 1997]. Shales fail readily, and the low-angle slopes or benches that they form are the repositories for colluvium, the source material for most debris flows (Figure 8) and another source of fine particles. Although the boulders that alter the river profile derive from the more massive or indurated, cliff-forming formations, the mechanism of debris flow that transports these particles to the river depends on the presence of softer, fine-grained shale formations in the canyon walls.

6. Modeling Debris Flow Frequency

[27] Given the long-term variability inherent in the frequency and magnitude of most hydrologic events, frequency measures are most effective when based on the longest possible record. The length of record becomes even more critical when the event being measured has a very long recurrence interval. Given a mean annual debris flow frequency of 5.0 events/year for 740 tributaries, the average recurrence interval for debris flow from any one tributary in Grand Canyon is 148 years. Use of the historic 100 year record of debris flow frequency at the Colorado River in Grand Canyon is limited by its restricted sample, only 20% of tributaries. By modeling this limited frequency record with drainage basin parameters observed to control the occurrence of debris flows at river level, we extend estimates of 100 year debris flow frequency to all 740 debris flow–producing tributaries in Grand Canyon. The multivariate statistical method of logistic regression was used to both identify those variables that are statistically significant and to calculate the probability of debris flow occurrence for each tributary in Grand Canyon.

6.1. Independent Variables

[28] Previous work on flood hazards in the region has focused on the statistical significance of various morphometric variables in relation to flood magnitude, usually emphasizing drainage basin area, mean basin elevation, and amount or intensity of precipitation [*Roeske*, 1978; *Thomas et al.*, 1997]. *Patton and Baker* [1976] suggest that stream order may also be a good predictor of flash flood potential for small drainage basins; they argue that transient controls, such as climatic variability, also play a significant role. *Shown* [1970] includes all of these variables in modeling sediment transport in the southwestern United States as well as factors relating to surface geology and soils such as rock type, hardness, weathering, and texture. *Mark* [1992] modeled the probability of debris flow occurrence for a single storm in San Mateo County, California, using observational variables such as storm precipitation, mean annual precipitation, source material, slope, and vegetation cover within a logistic regression model.

Table 2. Drainage Basin Variables Evaluated for Logistic Regression Modeling of Debris Flow Probability

Variable	Approximate Probability Distribution[a]	Range in Values	Units
Mean height above river			
Hermit Formation	bimodal normal	0–1353	meters
Supai Group	bimodal normal	0–1135	meters
Tonto Group	bimodal normal	0–891	meters
Rim of tributary	normal	414–2134	meters
Mean slope between river and			
Hermit Formation	bimodal normal	0–49.1	degrees
Supai Group	bimodal normal	0–53.4	degrees
Tonto Group	bimodal normal	0–51.2	degrees
Rim of tributary	normal	6.0–46.3	degrees
Total length of mapped faults	normal	−2.0–2.3	log (kilometers)
Mean elevation			
Hermit Shale[b]	bimodal normal	0–2073	meters
Supai Group[b]	bimodal normal	0–1951	meters
Muav Limestone[b]	bimodal normal	0–1707	meters
Rim of tributary[b]	normal	1061–2804	meters
Aspect			
Tributary	uniform	−1.0–1.0	none
River	uniform	0–1.0	none
Drainage basin area	uniform	−1.0–3.0	log (kilometers^2)

[a]For parameters with a bimodal normal distribution the distribution is normal, with a second peak at zero values.
[b]Elevation values correlated with height above river and were not included in logistic regression analysis.

[29] On the basis of our observations of debris flow initiation, we selected 16 drainage basin characteristics to evaluate as independent variables that control or influence the frequency of debris flows at the river in Grand Canyon (Table 2). Drainage basin area was included because we expect large tributaries to generate more debris flows. Large tributaries contain more source material and are more likely to intercept precipitation from localized thunderstorms than smaller tributaries. Larger drainages can also have more waterfalls and produce more runoff during widespread precipitation, especially those basins with large drainage areas above the canyon rim.

[30] Controls on the energy of failure and transport of debris flows are evaluated in terms of the height above the river and mean drainage basin gradient below the three principal source lithologies: the Hermit Formation, Supai Group, and Tonto Group (measured to bottom of the Muav Limestone) (Figure 8; Table 2). Other source areas, such as the Chinle Formation and Dox Sandstone, occur in isolated sections of the canyon and were not evaluated. Lithologic boundaries and elevations were identified from regional geologic maps [*Haynes and Hackman*, 1978; *Huntoon et al.*, 1981; *Billingsley and Huntoon*, 1983; *Huntoon et al.*, 1986] and 7.5′ U.S. Geological Survey topographic maps. Gradients were derived from a 10 m digital elevation model of Grand Canyon. Basin-wide energy controls were summarized by mean gradient and maximum height above the river for the entire drainage basin (Table 2). Although channel width is also a control on debris flow transport, this variable could not be effectively measured and was not included in the model.

[31] When a source lithology is not exposed in a given tributary, height and gradient were set at zero. In this manner the height and gradient variables also incorporate the presence/absence of the three primary source lithologies. Source material in Grand Canyon also occurs along the shear zones of fault-controlled drainages and may be more abundant where the density of faults is greater than normal. The influence of geologic structure in each drainage was evaluated as the linear sum of all surface faults as delineated on regional geologic maps (Table 2).

[32] Precipitation was the most difficult factor to quantify for debris flow initiation due to the sparse data available in the Grand Canyon area. In the absence of suitable data we used proxy variables derived from physical attributes of drainage basins that may influence local precipitation. Mean absolute elevation to the bottom of the three primary source lithologies and to the highest point in the drainage basin were included to reflect orographic effects on precipitation (Table 2). Both tributary and river aspect were also included to reflect steering of storm clouds through the canyon (Table 2). Drainage basin aspect is a morphometric variable that has been linked to precipitation and the generation of debris flows [*Pack*, 1985; *Church and Miles*, 1987]. In a deep canyon the river corridor, where parallel to the dominant path of weather systems and moisture vectors, may steer storm clouds and concentrate precipitation, particularly during thunderstorms. Tributaries in reaches where the river corridor is perpendicular to dominant storm directions may be orographically shielded. We measured the aspect (azimuth) of each tributary (from basin centroid to confluence) as well as the aspect of the canyon at each tributary confluence (averaged over 0.5 km of the river centerline) (Table 2). Both measures were referenced to the general southwest-northeast track of winter storms across the region by decreasing each aspect by 45°. These values were then linearized for compatibility with modeling process by taking the cosine of each tributary aspect and the absolute value of the cosine of each river aspect.

[33] Other variables known to influence debris flow occurrence elsewhere were not used due to their uniformity in Grand Canyon. Vegetation, for example, is extremely sparse at all source areas, and land use practices have minimal effects. Source sediment characteristics are also generally uniform, and most of the slope failures that generate Grand Canyon debris flows are not dependent on factors such as sediment permeability or porosity. Most variation in sediment characteristics is likely to be reflected

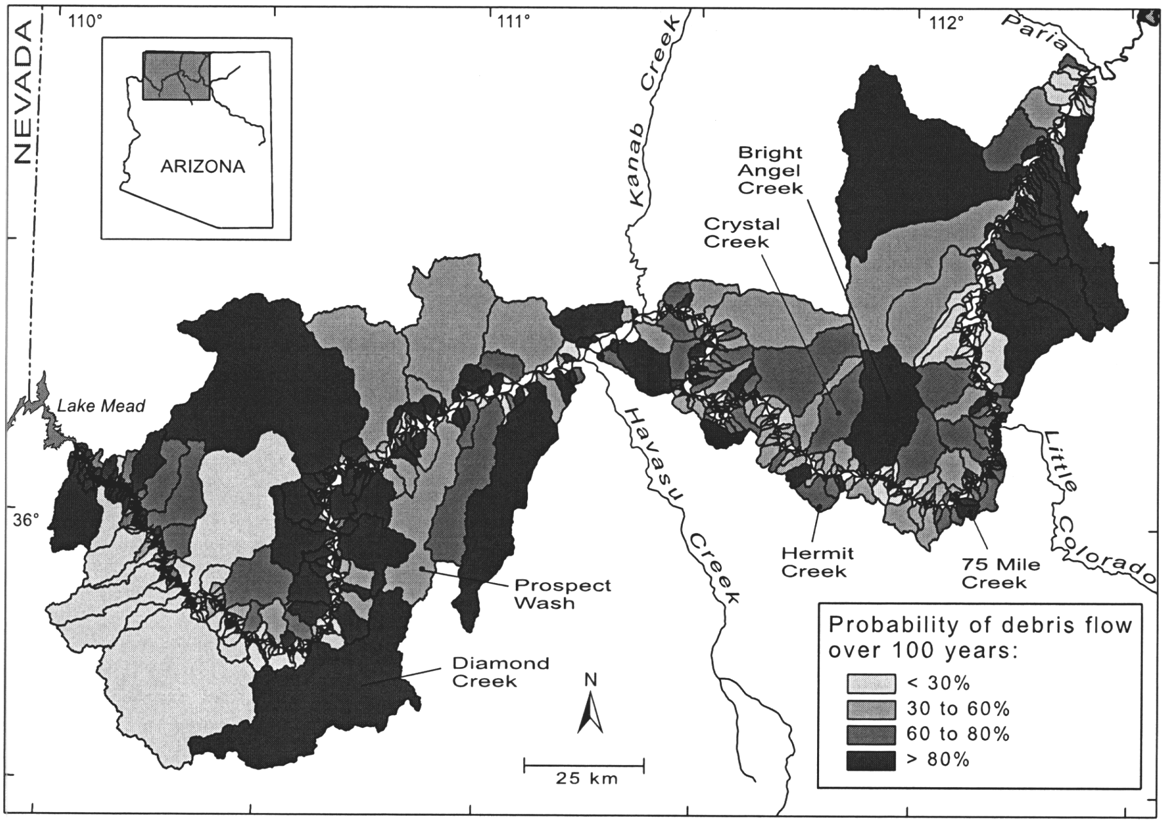

Figure 9. Map showing the probability of debris flow occurrence during the last century in 740 tributaries of the Colorado River in Grand Canyon, Arizona, calculated using logistic regression. See color version of this figure at back of this issue.

in the existing variables that distinguish source lithology (height and gradient).

6.2. Modeling Reaches

[34] Because of its spatial heterogeneity owing to the pattern of regional structure, Grand Canyon cannot be modeled as a single entity when estimating debris flow probability. *Griffiths* [1996] and *Webb et al.* [2000] divided Grand Canyon into eastern and western modeling reaches for statistical sampling, as opposed to geomorphic, reasons. Although our small sample size approaches the reasonable limits of logistic regression, the potential problems of dividing the sample into still smaller sets were outweighed by the benefits of reducing the variability being modeled. We separated the data into the large-scale geomorphic reaches of Marble Canyon (river miles 0–65), eastern Grand Canyon (river miles 65–143), and western Grand Canyon (river miles 143–280); the border between Marble Canyon and eastern Grand Canyon traditionally is the mouth of the Little Colorado River (river mile 61.5) (Figure 1). A comparison of the sample and population distributions of each drainage basin variable indicates that this division is statistically representative of the population of Grand Canyon tributaries.

6.3. Redundant Variables

[35] Although logistic regression will return useful results with any set of variables, physical interpretation of the model coefficients is simplified if covariation among the significant variables is minimized. Few drainage basin characteristics are completely independent from each other, and we evaluated all variables for interdependence. Variables for elevation strongly correlated with variables for height above river (R^2 ranged from 0.63 to 1.00 in all three reaches), and elevation was consequently dropped from the analysis. Height above river was retained in part as a proxy for elevation and its potential effect on precipitation but also as a measure of the presence of a given source material and potential energy of failure. All other variables were statistically independent, including gradient and height above river (R^2 ranged from 0.00 to 0.41 in all reaches). In a more homogenous setting, gradient would be expected to correlate strongly with height, but Grand Canyon tributaries vary widely in shape, ranging from nearly circular basins to long, linear canyons (Figure 9). Gradient for a given height varies as mean distance to the river varies with tributary shape.

6.4. Logistic Regression

[36] Multivariate logistic regression differs from multiple linear regression because the observed dependent variable is binary (either a specified event occurs, or it does not), and the model predicts the probability that the event will occur for a specific set of independent or controlling variables. We used logistic regression to model debris flow occurrence because the data is binary: for each tributary, either a debris flow occurred (outcome = 1) or did not occur (outcome = 0) between 1890 and the 1990s.

Table 3. Variables Used to Model the Probability of Debris Flow Occurrence on Reaches of the Colorado River in Grand Canyon, Arizona

Model Variables by Reach	Units	Variable Coefficients β_i[a]	Odds Ratio ψ[b]	Model Fit ρ_c[c]	Accuracy a (a_1/a_0),[d] %
		Marble Canyon (n = 33)			
Intercept (β_0)	na	−5.975	na	0.66	71 (77/59)
Drainage basin area	log (km^2)	4.675	66.9		
Height of Hermit Formation	m	−0.014	$(27.8)^{-1}$		
Gradient below Hermit Formation	deg	0.172	16.1		
Gradient below Tonto Group	deg	0.180	13.7		
Drainage basin gradient	deg	0.184	10.8		
Height of drainage basin rim	m	−0.006	$(6.9)^{-1}$		
River aspect	none	3.759	2.8		
		Marble and Eastern Grand Canyon (n = 66)			
Intercept (β_0)	na	−1.982	na	0.32	60 (67/49)
Height of Hermit Formation	m	−0.003	$(4.9)^{-1}$		
Gradient below Tonto Group	deg	0.098	3.5		
Gradient below Hermit Formation	deg	0.074	3.4		
Gradient below Supai Group	deg	−0.043	1.8		
River aspect	none	1.790	1.7		
Drainage basin area	log (km^2)	0.704	1.7		
		Western Grand Canyon (n = 48)			
Intercept (β_0)	na	−0.341	na	0.78	68 (68/68)
Height of Tonto Group	m	−0.017	$(19.6)^{-1}$		
Height of Supai Formation	m	0.007	9.9		
Gradient below Supai Group	deg	−0.149	$(7.5)^{-1}$		
Drainage basin gradient	deg	0.137	3.2		
Height of Hermit Formation	m	0.002	2.3		

[a]Variable coefficients for the logistic regression model calculating the probability of debris flow occurrence for each tributary in the model reach.

[b]The odds ratio (ψ) gives the ratio by which the odds that a debris flow will occur will increase if the variable value increases by one unit. These statistics were calculated for standardized variables with a unit of 1σ ($\mu = 0$ and $\sigma = 1$) so that the odds ratios, and thus the effects of each variable on the model, can be directly compared. Variables are listed in order of effect on the model, the variable with the largest effect first. Odds ratios <1 are presented as $(1/\psi)^{-1}$ to emphasize the magnitude of their effect on the odds.

[c]Significance of the *Hosmer and Lemeshow* [1989] goodness-of-fit statistic for the model. A higher value indicates greater fit to observed data.

[d]Percentage of observed tributary outcomes that are correctly predicted by the model. Accuracy in predicting the occurrence (a_1) and nonoccurrence (a_0) of debris flows are given in parentheses.

For logistic regression the conditional mean ($\pi(x)$), or probability, of an event occurrence is

$$\pi(x)\frac{e^{\beta_0+\beta_1x_1+\beta_2x_2+\ldots+\beta_ix_i}}{1-e^{\beta_0+\beta_1x_1+\beta_2x_2+\ldots+\beta_ix_i}}, \qquad (1)$$

where x is an independent variable, β is the variable coefficient, and i is the total number of independent variables. The modeling process defines values of β for each independent variable [*Hosmer and Lemeshow*, 1989] to fit $\pi(x)$ to the observed data. Log-normally distributed independent variables (drainage basin area and fault length) were log transformed to normalize their distribution in the modeling process.

[37] Independent variables were evaluated for the statistical significance of their contribution to model results. The null hypothesis that a given variable contributes nothing to the model outcome ($\beta_1 = 0$) was evaluated using a chi-square-based significance measure, ρ_v (derived from the likelihood ratio, G [*Hosmer and Lemeshow*, 1989]). We used a threshold of $\alpha = 0.20$ to identify nonsignificant variables. In an iterative, backward-step process we began with all 16 independent variables, removed the variable with the greatest ρ_v, created a new model, again removed the least significant variable, and repeated the process until only variables with a model significance <0.20 remained. Using a lower, more rigorous threshold (e.g., $\alpha = 0.10$) resulted in models with few geomorphically meaningful variables.

[38] Model fit to the observed data was evaluated with three statistical measures, as described in the footnotes of Table 3. Accuracy (a) is the percentage of correctly predicted debris flow occurrences. The *Hosmer and Lemeshow* [1989] goodness-of-fit statistic (ρ_c) measures the statistical significance of differences between observed and modeled results on a scale of 0–1 and is a more precise measure of overall model fit than a. Finally, the standardized odds ratio (ψ) was used to evaluate model sensitivity to each of the significant variables (Table 3). Typically, ψ for an independent variable gives the increase in the odds of an event occurrence for an increase in the independent variable of one unit. For example, $\psi = 2$ for the height of the Hermit Formation indicates that a 1 m increase in the Hermit Formation will increase the odds of debris flow occurrence by 2:1. In order to compare variables with different units, we standardized ψ to represent the increase (or decrease for $\psi < 1$) of the odds of occurrence for a change in the variable of 1σ.

6.5. Model Results

[39] The logistic regression models for Marble and western Grand Canyon fit the observed data moderately well ($\rho_c = 0.66$ and 0.78), with a fair accuracy ($a = 0.71\%$ and 68%) (Table 1). Model results for eastern Grand Canyon were poor because only two variables, river aspect and tributary aspect, were significant, model fit was poor ($\rho_c = 0.11$), and the accuracy was limited ($a = 0.56$). Although its sample size is the largest of all the reaches (66 tributaries),

eastern Grand Canyon has a more complex array of geomorphic factors determining debris flow occurrence at the river, and logistic regression was unable to incorporate these factors into an efficient model. Effective modeling of this reach likely requires a data set large enough to be split into smaller reaches representative of the varied geomorphic setting, such as local exposures of shale formations in the Grand Canyon Supergroup (Figure 4). In order to reduce the variability of these data, we combined eastern Grand Canyon with Marble Canyon, and the resulting model fit ($\rho_c = 0.32$) was a substantial improvement. Both the Marble Canyon and eastern Grand Canyon models did better at predicting debris flow occurrence than nonoccurrence (a_1 = 77% and 67%, and a_0 = 59% and 49%, respectively) and therefore may overpredict the occurrence of debris flows. The model for western Grand Canyon was equally successful in predicting observed debris flows and nonoccurrence.

[40] Variables associated with the Hermit Formation and Tonto Group were significant in all three models, emphasizing the importance of these two source lithologies in initiating debris flows that reach the river throughout the canyon. Changes in the odds ratios reflect the expected variation of the influence of the Hermit Formation and Tonto Group as the units sequentially rise in the stratigraphic section downstream (Table 3). The Hermit Formation was the most influential source variable in Marble Canyon, was in rough parity with the Tonto Group in eastern Grand Canyon, and then was least influential in western Grand Canyon, where the Hermit Formation is far from the river. The mean gradient to the river from these two source lithologies are each positively correlated with increased debris flow frequency at the river in each reach.

[41] Height above the river of the Hermit Formation and Tonto Group was negatively correlated, with increased debris flow frequency in almost all reaches (Table 3). This suggests that the orographic effects of increased precipitation with elevation do not significantly affect the frequency with which debris flows reach the river. Also, the threshold of failure energy is likely sufficiently small in comparison to the total range of source area heights that it does not affect this variable significantly. Instead, this negative correlation likely reflects the increased likelihood that debris flows will reach the river when the source area is closer to the river. The one exception to this correlation is the Hermit Formation in western Grand Canyon, which is negatively correlated with increased frequency. Here this formation is so high above the river that it is not present at all in smaller drainage basins, and the height of unit has a bimodal distribution: absent or high in the canyon walls. In order to affect debris flows, the Hermit Formation must be present and therefore high above the river.

[42] Supai Group variables were retained as significantly associated with increased debris flow frequency in eastern and western Grand Canyon (Table 3). The retention of these variables is consistent with the bedrock failure mechanism that typically occurs in the Supai Group. Bedrock failures produce the fewest debris flows, and Supai variables do not strongly influence debris flow frequency in the models. Bedrock failure is consistent with the morphology of the Supai Group, which consists of more cliff-forming components and consequently stores less colluvium than the other two primary source lithologies. This morphology and failure mechanism may explain the correlation of Supai height (positive) and gradient (negative) to increased debris flow frequency at the river, which is the inverse of the correlations of the other two lithologies. Bedrock failures typically produce high-energy, high-magnitude debris flows triggered in high-angle cliff faces that are less susceptible to the controls of channel width and gradient [*Melis et al.*, 1994]. Consequently, high-angle bedrock failures in the Supai are more likely to be influenced by total gravitational potential energy of the source lithology than smaller, low-angle colluvial failures in the Hermit Formation and Tonto Group.

[43] Variation in drainage basin morphology by reach is apparent in the selection of drainage basin area and gradient in the three models. In Marble Canyon, large areas and steep gradients are linked with more debris flows, reflecting an uncomplicated morphology of tributaries cut into a steep-sided canyon. In western Grand Canyon, debris flow frequency decreases with drainage basin area, in part because only extremely large debris flows can transit the relatively low-gradient channels of the largest tributaries to reach the Colorado River.

[44] Local aspect of the river corridor was a significant independent variable in Marble Canyon and eastern Grand Canyon (Table 3). This was the only proxy variable for precipitation that was selected (most height variables were inversely correlated with debris flow occurrence). In both models a southwest-northeast orientation of the river, parallel to the prevailing storm track, was correlated with increased debris flow frequency at the river. Notably, this was among the least influential variables in both models and so is not as strong a control on debris flow frequency at the river as lithologic and morphologic variables. Nevertheless, its statistical significance suggests the possibility of a link between canyon aspect and precipitation, though proof of this connection will depend on future research, possibly involving weather radar that would provide a regional perspective lacking in the sparse precipitation gauge network. It is also likely that this influence only occurs at the larger scale of the river canyon as tributary aspect was not selected as significant. One alternative may be that this variable is linked to regional faults, many of which trend in the same direction. However, the density of faulting is not a significant variable in any model. Clearly, fault-derived source material is locally important in several drainages within Grand Canyon, but it is not a significant contributor in the overall pattern of debris flow probability.

7. Discussion and Conclusions

[45] Debris flows in Grand Canyon control the geomorphic framework of the Colorado River by depositing large boulders that alter rapids and locally modify the river's longitudinal profile. Both recent (1984–2003) and historic (1890–1983) data sets record a mean frequency of about 5.0 debris flows/year reaching the Colorado River from 740 tributaries. These mass movements are initiated when weathered bedrock or colluvial wedges fail during intense rainfall. Most failed material is unsaturated and requires sufficient initial transport energy to mix with water in transit and form a debris flow. Once debris flows have formed, transport distance is limited primarily by the energy restrictions of gradient and channel width.

[46] Failures that form debris flows that reach the Colorado River can be classified according to four failure mechanisms, all of which are related to the locations of shale units within the tributary, primarily in the Hermit Formation, Supai Group, and Tonto Group. Shales fail readily as weathered bedrock, produce abundant colluvial source material, and form slopes where colluvium accumulates. Shales also provide the fine particles and clay minerals that are essential to long-distance transport (up to 22 km) of large particles from tributary sources to the Colorado River. Therefore although the overall gradient of the river is controlled on a regional scale by bedrock, the longitudinal profile of the present-day river is controlled locally by the weakest geologic strata in Grand Canyon, not the resistant strata at river level as proposed by *Powell* [1875].

[47] Logistic regression modeling of historic (1890–1983) debris flow frequency identifies several drainage basin parameters that are significantly related to the occurrence of debris flows at river level. Significant parameters include the presence of and drainage basin gradient below primary shale source lithologies as well as drainage basin area, mean drainage basin gradient, and the aspect of the river corridor. Frequency calculations from the logistic regression model demonstrate that debris flows that reach the river in Grand Canyon are not randomly distributed in space (Figure 9). The occurrence of debris flows is greatest in eastern Grand Canyon, where 64% of the tributaries have had a probability of debris flow occurrence greater than 50% during the last century; debris flow frequency in western Grand Canyon is a similar 62%, whereas in Marble Canyon, only 47% of the tributaries have a probability greater than 50%. In contrast, the recent (1984–2003) record shows that 15% of tributaries in Marble Canyon had debris flows, while only 5% of tributaries in western Grand Canyon had events from 1984 through 2003. However, debris flows have occurred in 18% of tributaries in eastern Grand Canyon over the last 20 years, in accord with the calculated probabilities. The discrepancy between the recent record and calculated historic probabilities is likely a result of the different record lengths; the geographic distribution of debris flows varies annually, and eastern Grand Canyon may outpace Marble Canyon over the next 80 years.

[48] Drainage basin variables that are most significant in influencing the occurrence of debris flows that reach the river are also illustrated in the distribution of modeled debris flow probabilities (Table 3; Figure 9). Most obvious is the tendency for debris flow frequency to decrease when the river corridor trends away from a southwesterly course. The effect of drainage basin area is evident in Marble Canyon, where the largest tributaries have high probabilities of debris flow occurrence at the river (most >0.6). The gradient and height of the Hermit Formation, which is significant in all three models, appears to be especially important in Marble Canyon and reflects the dominant contribution of shale units to debris flows in Grand Canyon.

[49] In eastern Grand Canyon a greater variety of source materials, combined with structural heterogeneity, result in a patchwork of debris flow probabilities. The presence of and gradient below clay-bearing strata is paramount to debris flow probability, and river aspect and drainage area are significant but less influential. Certain sections of river corridor that trend northwesterly generally have tributaries with low (<0.3) debris flow probabilities (Figure 9). In western Grand Canyon the three source lithologies as well as the overall gradient of each drainage basin strongly influence debris flow occurrence. The height of the Hermit Formation is the least influential of the lithologic variables due to the fact that this formation is farther from the river than in either eastern Grand Canyon or Marble Canyon. Debris flow probability is lowest downstream from Diamond Creek (Figure 1), where the river trends northwesterly. The exception is in the reach immediately upstream from the Grand Wash Cliffs, where debris flow probabilities are predicted to be high despite a northwesterly trend (Figure 9).

[50] The results of the logistic regression model demonstrate that variation in lithologic, morphometric, and climatic variables have a strong effect on the probability of debris flows along the Colorado River in Grand Canyon. Our results differ from those of *Mark* [1992], who found that debris flow occurrence during one rainstorm was mostly related to slope and climatic variables, though in a different climatic and lithologic setting. Instead, debris flows that reach the river in Grand Canyon are related, both observationally and statistically, to the presence of shale units within the tributary drainage basins as well as topographic and climatic factors.

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P. G. Griffiths and R. H. Webb, U.S. Geological Survey, 1675 W. Anklam Road, Tucson, AZ 85745, USA. (pggriffiths@usgs.gov; rhwebb@usgs.gov)

T. S. Melis, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA. (tsmelis@usgs.gov)

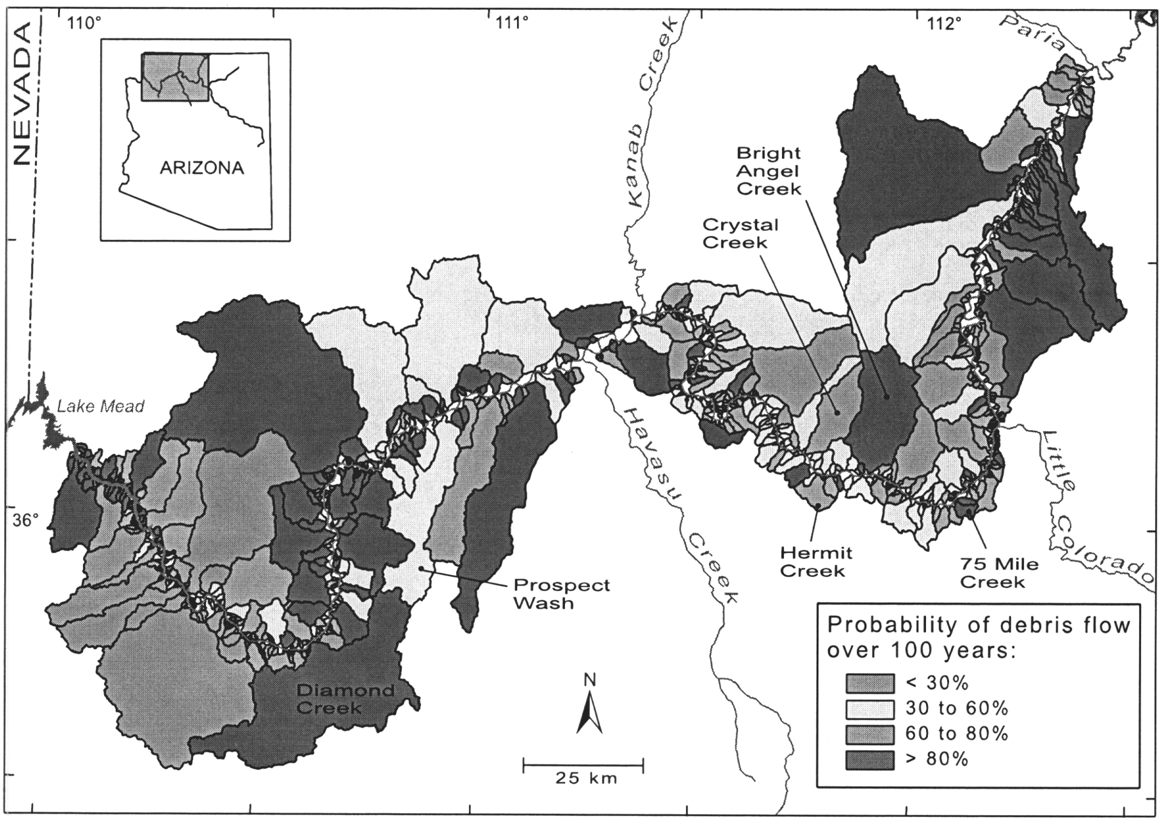

Figure 9. Map showing the probability of debris flow occurrence during the last century in 740 tributaries of the Colorado River in Grand Canyon, Arizona, calculated using logistic regression.